Chapter 2
General Description

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Abstract Africa and Latin America possess tremendous potential for significant growth of renewable energy. Much of this potential is derived from access to large land areas with more than 37% of the combined global surface area, the availability of abundant renewable resources (i.e., wind, water and solar), commitments to cut global emissions by 2030 and a growing recognition by some nations that low carbon energy development enhances economic prosperity. Moreover, Africa and Latin America produce more than 23% of the global renewable energy, but much of this energy is provided by traditional biofuels (36% of total global production) to support daily sustenance needs (i.e., heating and cooking) rather than electricity production. An energy paradox exists for Africa and Latin America as they have diverse and often abundent energy reserves that vary between nations but they seldom achieve generation levels necessary for growth of national or regional economies. In this chapter a general description of both regions is provided. This description incorporates updated key parameters that should influence present and future energy decisions by governments, business sector, researchers and professionals including primary energy supply, reserves, carbon emissions versus GDP, water consumption, land consumption, easiness of doing business, etc. As the ease of transactions within the business environment improves there is likely to be greater diversification of energy sources and an overall expansion of entrepreneurial activities.

Keywords Africa · Latin america · Energy · Electricity · Renewable technology · Power plants · CO_2 · Carbon emissions · Carbon capture · CCS · Coal · Oil · Natural gas · Combustion · Energy storage · Water · Fossil fuels

2.1 Introduction

The global potential for the production of renewable energy resources is huge and exceeds the world total primary energy supply (TPES) based on conventional energy resources for each primary renewable energy resource (Fig. 2.1). The renewable energy resource with the largest potential (considering only the surface

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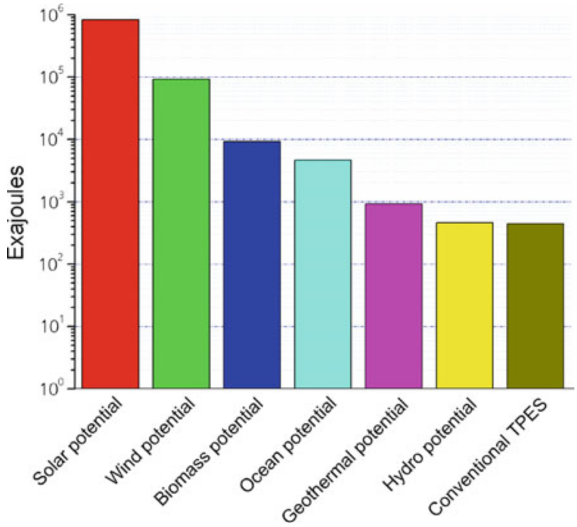

Fig. 2.1 Global technical potential for the different renewable energy resources, compared to the world conventional annual TPES in 2014 [4]

land above the sea level) is solar energy, followed by wind energy. Much of the technical potential for renewables is located in Africa and Latin America, as these regions represent 22 and 15%, respectively, of the world surface area (i.e., 134,324,741 km^2) [1], and comprise 15.2 and 8.5% of the world's population (i.e., 7.35 billion inhabitants) (2015) [2]. Africa represents 5.64% of the 572 Ej (2014) world total primary energy supply (TPES: indigenous production + imports – exports − international marine bunkers − international aviation bunkers ± stock exchanges) and Latin America 6.31% [3].

In Africa, the actual percentage of renewable energy used is huge compared to the rest of the world (Table 2.1) and in Latin America it is substantial. Renewable energy in both of these region is primarily associated with biofuels and the basic sustenance needs of heating and cooking rather than the growth of modern renewable technologies for producing electricity and reflects the limitations on the deployment of energy infrastructure throughout these regions. Fossil fuels play a significant role in each region, nuclear energy is present in both regions and hydropower is substantial in parts of Latin America (Table 2.1).

In relation to the proven reserves and average annual consumption of the different fossil fuel resources [5] and uranium [6], the most updated statistics indicate that proven reserves of fossil fuels are adequate in both regions for meeting the current demand and average consumption growth (Table 2.2).

Energy consumption per capita (Table 2.3) for both regions is well below global averages, reflecting the significant gap between these regions and the most advanced regions in the world relative to energy consumption per capita. This situation can be considered as an opportunity to move Africa and Latin America to a more sustainable energy supply system based on low carbon technologies.

Table 2.1 Main TPES (EJ) indicators for Africa, Latin America and the World in 2012 (last data available) [3]

TPES 2014 (Mtoe)	World	Africa	Latin America
Coal	164	5	2
Crude oil	182	5	15
Natural gas	121	5	9
Nuclear	27	0.2	0.3
Hydro	14	0.4	3
Geothermal, solar, etc.	8	0.2	0.4
Biofuels and waste	59	15	6
Total	575	32	36
% world renewables/total	14	49	26

Table 2.2 Proven reserves of oil, coal and natural gas, known recoverable reserves of uranium, consumption, increase in consumption and proven reserves in year terms [5, 6]

Proven reserves	World	Africa	Latin America
Proven reserves oil (billion barrels, 2015)	1663	127	340
Proven reserves coal (million short tonnes, 2014)	1,071,560	14,640	16,785
Proven reserves natural gas (trillion cubic feet, 2015)	6950	604	291
Known recoverable uranium (thousand tonnes, 2013)	5903	1253	276
Oil consumption (thousand barrels per day, 2013)	91,195	3601	6628
Coal consumption (million short tonnes, 2011)	8186	221	50
Natural gas consumption (billion cubic feet, 2013)	121,357	4573	4698
Uranium production (tonnes, 2013)	59,673	10,505	198
% consumption oil (2004–2013)	1.31	2.79	3.49
% consumption coal (2003–2012)	4.20	1.76	4.19
% consumption natural gas (2003–2013)	2.61	5.91	3.93
% production uranium (2003–2013)	5.30	5.87	-3.13
Reserves oil (years)	39	48	51
Reserves coal (years)	44	77	65
Reserves natural gas (years)	36	26	31
Reserves uranium (years)	36	37	–

Table 2.3 Fossil fuel consumption per capita (2014)

	World	Africa	Latin America
Consumption per capita oil (barrel/year)	4,62	1,20	3,93
Consumption per capita coal (short tonnes/year)	1,14	0,20	0,08
Consumption per capita natural gas (thousand cubic feet/year)	16,84	4,17	7,63

2.2 Carbon Emissions and Climate Change

If we consider the thermodynamic balance of a planet at a constant temperature, the amount of absorbed energy as solar radiation must equal the amount of energy emitted back to space at longer wavelengths (infrared). On Earth, re-emitted radiation reaches 239 W/m^2. According to thermodynamics, a body emitting energy with this power density would have a mean temperature of −18 °C. However, the average temperature on Earth is larger due to the presence of greenhouse gases in the atmosphere, which absorb and re-emit infrared radiation while keeping the lower atmosphere and the Earth's surface warm (Fig. 2.2) [7].

The increase in global energy consumption associated with increased economic development in recent decades is also related to the increase in annual CO_2 emission rates (Fig. 2.3) [5]. Global economic recessions related to the economic crises in 1974, 1980–82, 1990 and 2008–09 are readily apparent as small reductions in annual CO_2 emission rates (Fig. 2.3).

Carbon is emitted but also absorbed on a global scale. A global carbon budget published in the literature (Table 2.4) [8] suggests that fossil fuels and cement are increasing their shares in global CO_2 emissions while established forests are decreasing their role as CO_2 sinks (although the overall effect of deforestation is to warm the planet, replacing the trees with crops or grassland makes the ground paler and more reflective, and particles created from sulphur oxide reflects light into space [9]). Consequently, the atmosphere is increasing in its share of the carbon budget resulting in an increase in atmospheric CO_2 content.

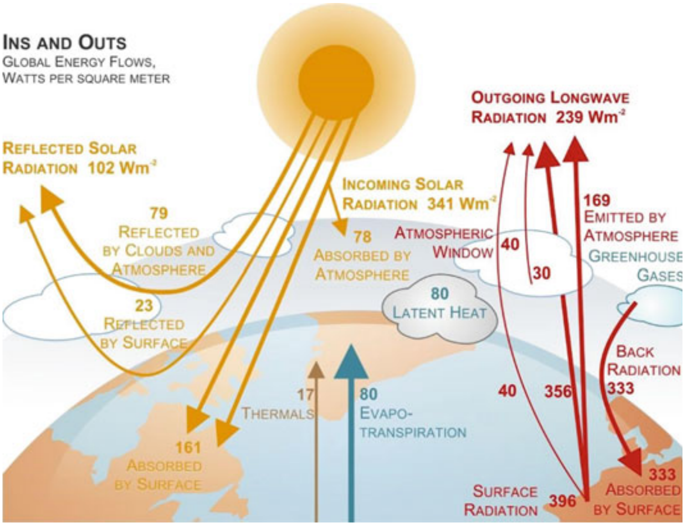

Fig. 2.2 Description of the thermodynamic balance on Earth [5]

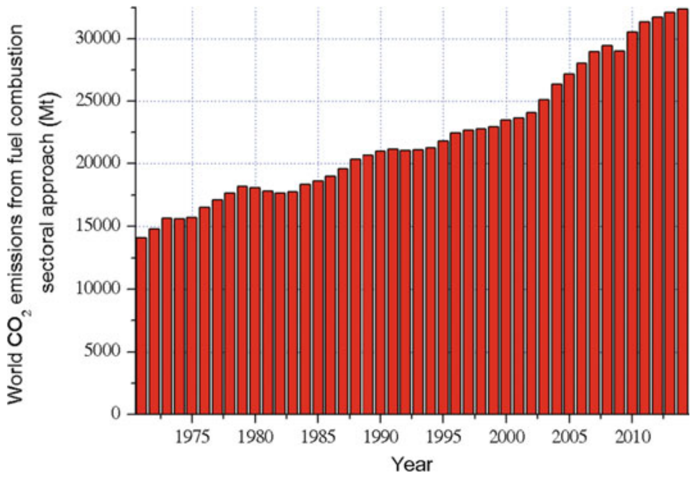

Fig. 2.3 Evolution of the world's annual CO_2 emission rates in the period 1978–2014 [3]

Table 2.4 Global carbon budget decomposed in terms of sources and sinks, and calculated for the periods 1990–1999 and 2000–2007 [8]

Pg CO_2/year	1990–1999	2000–2007
Sources (CO_2 emissions)		
Fossil fuel and cement	6.5 ± 0.4	7.6 ± 0.4
Land-use change	1.5 ± 0.7	1.1 ± 0.7
Total sources	8.0 ± 0.8	8.7 ± 0.8
Sinks (CO_2 absorption)		
Atmosphere	3.2 ± 0.1	4.1 ± 0.1
Ocean	2.2 ± 0.4	2.3 ± 0.4
Terrestrial (established forest)	2.5 ± 0.4	2.3 ± 0.5
Total sinks	7.9 ± 0.6	8.7 ± 0.7
Global residuals	0.1 ± 1.0	0.1 ± 1.0

Increasing CO_2 emissions to the atmosphere is causing the average CO_2 levels in the atmosphere to rise very significantly, from the 280 ppm in the pre-industrial era to above 400 ppm currently measured (Fig. 2.4) [10].

The increasing CO_2 levels in the atmosphere is reducing the Earth's radiation of heat into space and, consequently, producing an increase in the average global temperature [11, 12]. Under these conditions, temperature increases of around 0.15 °C per decade are estimated [12]. Global warming is not only associated with direct changes in weather conditions and subsequent food availability [7, 13], but also with an increase in extreme weather events [14, 15] and even civil conflicts [16].

Experience over the last several decades shows that the implications of projected global mean temperature changes tends to underestimate regional (and national level) impacts because the global changes are much smaller than the expected changes on average and extreme regional temperatures occur over most land areas.

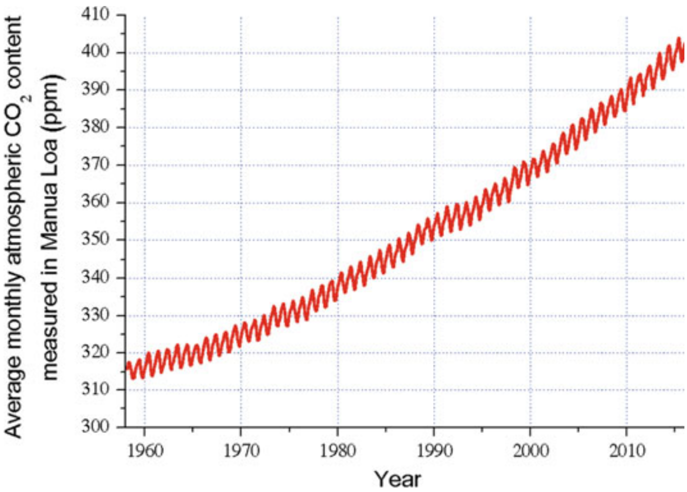

Fig. 2.4 Average monthly atmospheric CO_2 content measured at Mauna Loa Laboratory (Hawaii) [10]

Thus, models show these enhanced changes in many areas of Africa and Latin America [17].

Technological advances in the energy sector will help reduce atmospheric CO_2 emissions. For example, the replacement of coal fired power plants by natural gas combined cycle power plants (Fig. 2.5), or nuclear power plants, and carbon capture and sequestration techniques can reduce emissions. However, it is obvious that

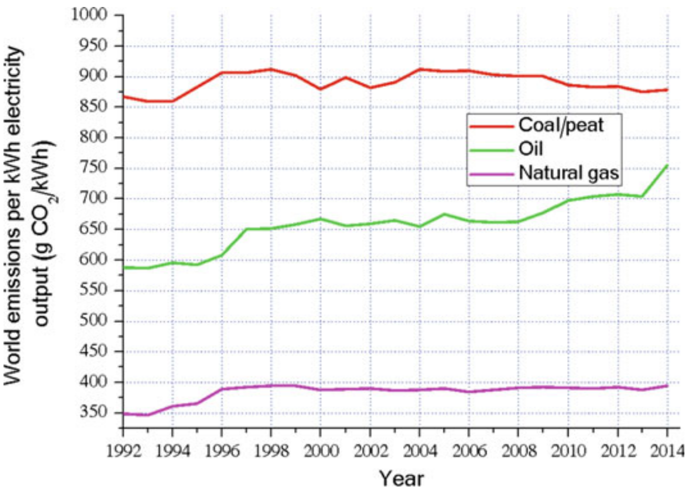

Fig. 2.5 Evolution of CO_2 emissions per kWh of electricity produced by conventional plants fired with coal, oil or natural gas [3]

significant reductions in CO_2 emission rates from the energy sector is a complex challenge and will require a systems solution that includes a combination of improving energy efficiency, replacing conventional technologies with renewables, and significant investments in infrastructure, education and outreach, among others.

The Kyoto Protocol has identified several measures to encourage large industries to reduce their CO_2 emission rates. One of the most popular measures has been the creation of a market for carbon emission permits to incentivize more efficient energy consumption and to improve the technologies used in industrial processes. However, the price evolution of the emission permits in the most important market, the EU Emission Trading Scheme, has been below initial expectations (Fig. 2.6) [18], generating very little incentive to reduce CO_2 emissions or to introduce new technologies to capture and store CO_2. However, some estimates indicate that this market has facilitated the reduction in CO_2 emissions by a few percentage points per year compared to a scenario without any permit market [19].

A new policy recently approved to reduce global carbon emissions is derived from the Paris Climate Change Conference on November 2015. After this summit, most African and Latin American countries have submitted their Intended Nationally Determined Contribution (INDC) to cut global GHG emissions by 2030 to the United Nations (Table 2.5) [20]. However, most targets are directly or indirectly tied to foreign support. For less developed countries, limited confidence exists in the data available to support key decisions on the policies to be implemented.

South Africa is currently deliberating the introduction of a carbon tax which has become quite controversial because of the large financial implications for the national utility (Eskom) and the mining sector [21]. Conversely, Zambia has imposed a carbon tax on all motor vehicles since 2006 [21].

Fig. 2.6 Evolution of the daily CO_2 emission permits price in the EU Emission Trading Scheme [18]

Table 2.5 Intended national determined contributions in Africa and Latin America to cut global GHG emissions by 2030 [20]

Country	%	Reference
Angola	35	BAU_{2005}
Benin	3.5	2016
Botswana	15	2010
Burkina Faso	6	BAU_{2030}
Burundi	3	BAU_{2030}
Cameroon	35 (C)	2010
Cabo Verde	20 (C)	BAU_{2030}
CAR	5 (C)	BAU_{2030}
Chad	18.2	BAU_{2030}
Congo	48 $(C)_{2025}$	BAU_{2025}
Côte d'Ivoire	28	2012
DR Congo	17 (C)	2000
Djibouti	40	BAU_{2030}
Eq. Guinea	20 (C)	2010
Eritrea	39.2	BAU_{2030}
Ethiopia	64	BAU_{2030}
Gabon	50	BAU_{2025}
Gambia	45.4	BAU_{2030}
Ghana	15	BAU_{2030}
Guinea	13 (C)	1994
Kenya	30 (C)	BAU_{2030}
Lesotho	10	BAU_{2030}
Liberia	15	BAU_{2030}
Madagascar	14 (C)	BAU_{2030}
Malawi	30 (C)	2015
Mali	31.6 (C)	BAU_{2030}
Mauritania	2.7	BAU_{2030}
Morocco	32 (C)	BAU_{2030}
Namibia	89 (C)	BAU_{2030}
Niger	3.5	BAU_{2030}
Nigeria	20	BAU_{2030}
Tanzania	10–20 (C)	BAU_{2030}
Togo	11.14	2010
Tunisia	41 (C)	2010
Uganda	22	BAU_{2030}
Zambia	47 (C)	BAU_{2030}
Zimbabwe	33 (C)	BAU_{2030}
Argentina	15	BAU_{2030}
Brazil	43	2005
Chile	30	2007
Colombia	20	BAU_{2030}

(continued)

Table 2.5 (continued)

Country	%	Reference
Costa Rica	25	2012
Dominican R	25 (C)	BAU_{2030}
Ecuador	20.4 (C)	BAU_{2030}
Guatemala	11.2	2005
Haiti	5	BAU_{2030}
Honduras	15 (C)	BAU_{2030}
Mexico	25	BAU_{2030}
Paraguay	10	BAU_{2030}
Peru	20	BAU_{2030}
Venezuela	20 (C)	BAU_{2030}

BAU Business as usual; *C* Conditional to international support

2.3 Low Carbon Development Concept

The *low carbon development* concept is an explicit strategy to increase GDP per capita while simultaneously decreasing the carbon emissions related to the consumption of energy. A comparison of GDP per capita and CO_2 emissions per capita [1] for the different countries in Africa and Latin America (Figs. 2.7 and 2.8) shows a logarithmic relationship between GDP and CO_2 emissions. For most countries since 2000, as GDP increases, CO_2 emissions increase. However, some countries have been capable of increasing their GDP per capita and reducing their CO_2

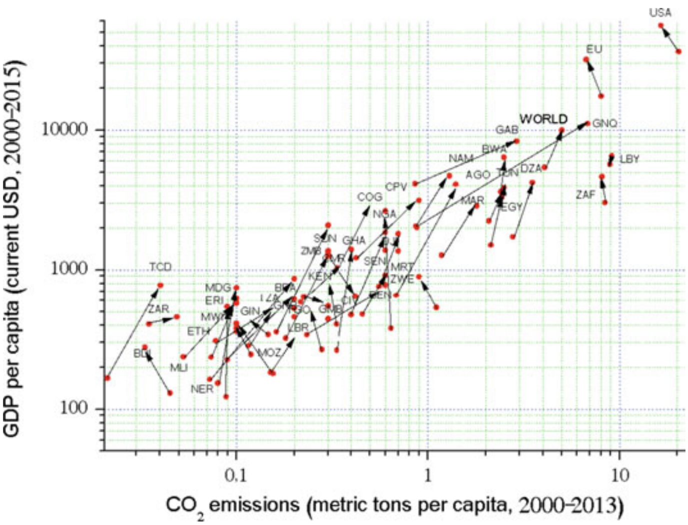

Fig. 2.7 GDP per capita (2000–2015) versus CO_2 emissions per capita (2000–2013) in the African countries from 2000 to 2013 [1]

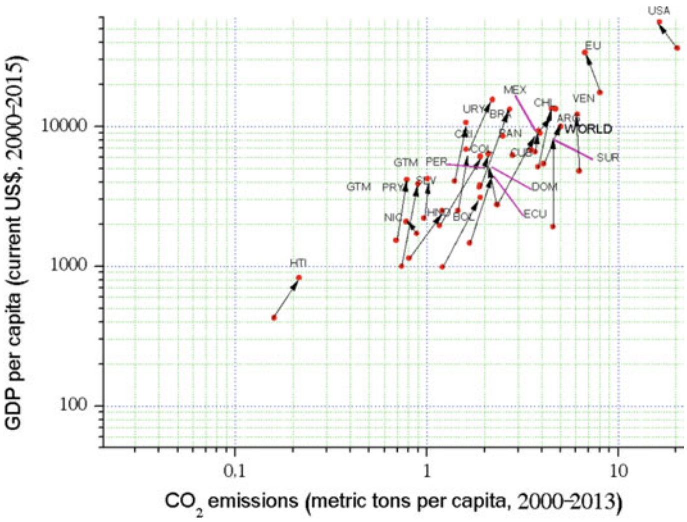

Fig. 2.8 GDP per capita (2000–2015) versus CO_2 emissions per capita (2000–2013) for Latin American countries from 2000 to 2013 [1]

emissions (e.g., Burundi, Eritrea and Zimbabwe in Africa and the Dominican Republic, Suriname and Venezuela in Latin America), in part because their economies are very limited.

In contrast to the most common evolution of GDP per capita and CO_2 emissions per capita in Africa and Latin America, the trends in the European Union (EU) and USA show low carbon development dynamics. Thus, it is possible to grow in terms of GDP per capita in parallel to a lower consumption of fossil fuels for countries showing high GDP values. This behaviour is encouraging not only because it means that increases in living standards can be reached without increasing global CO_2 levels, but also because this growth is mostly based on indigenous energy resources. Africa and Latin America, both regions with under average energy consumption per capita (Table 2.3), have a huge opportunity to increase their GDP mainly based on the penetration of low carbon indigenous energy technologies.

The principal environmental impacts associated with the development of the energy sector in emerging nations include increasing CO_2 emissions, water consumption and land use. Since the impacts from each technology are affected differently by external constraints (e.g., location, energy mix, variations in the prices of raw materials, etc.) there are not well established methodologies for calculating specific impacts. However, general guidance is available for most renewable technologies that can be used to estimate relative environmental impacts.

The production of electricity with any renewable technology produces CO_2 emissions when the entire technology life cycle is considered (Fig. 2.9) [22]. The manufacture of renewable energy technologies requires energy, and today this energy is usually supplied by a power grid where fossil fuels play a major role.

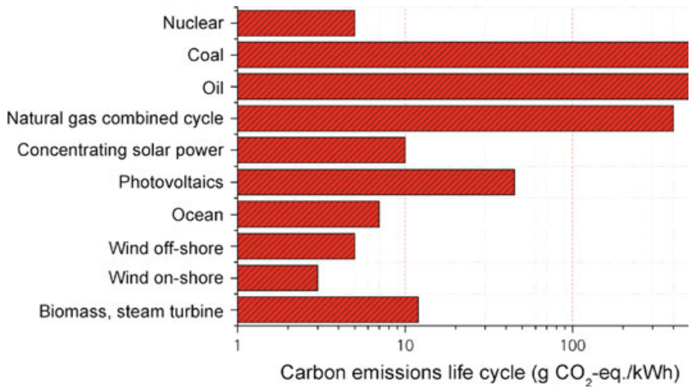

Fig. 2.9 CO_2 emissions per kWh of electricity produced from different renewable energy technologies considering the full lifecycle of these systems [22]

Many of the materials that integrate the renewable energy technologies into power plants (cement, steel, aluminum, etc.) are also produced with energy supplied from power grids or heating systems where fossil fuels play an important role. In the long term, life cycle CO_2 emissions will decrease as the contribution of renewable energy to total energy consumption increases in those regions where the manufacturing, construction, operations, maintenance and disposal of renewable power plants become increasingly free of carbon emissions.

The largest CO_2 emitters per kWh produced are coal-fired power plants, well above the emissions from renewable technologies. Recent studies also suggest that crude-oil extracted from oil sands by new procedures increases air pollution with respect to established estimates as observed in the crude extracted from the Canadian oil sands [23].

Another important environmental impact is water consumption per kWh produced by different energy technologies. Water production can require large amounts of energy in many locations for water transport, distribution and treatment. As observed in Fig. 2.10 [24], water consumption for wind energy and photovoltaics is almost negligible but is substantial for other renewable technologies, mainly hydropower and geothermal. Conventional power plants are also important water consumers, with coal fired power plants the largest water consumer. This result, added to the fact that coal fired power plants are the larger carbon emitters of all power plant technologies (Fig. 2.10), makes coal the leading technology in terms of environmental impact. Recent studies conclude that the energy return from water invested for the most water-efficient fossil fuel technology is one or two orders of magnitude greater than the most water-efficient biomass technologies [25]. Hence, the development of biomass energy technologies could produce or exacerbate water shortages around the globe, and this effect should be further analysed.

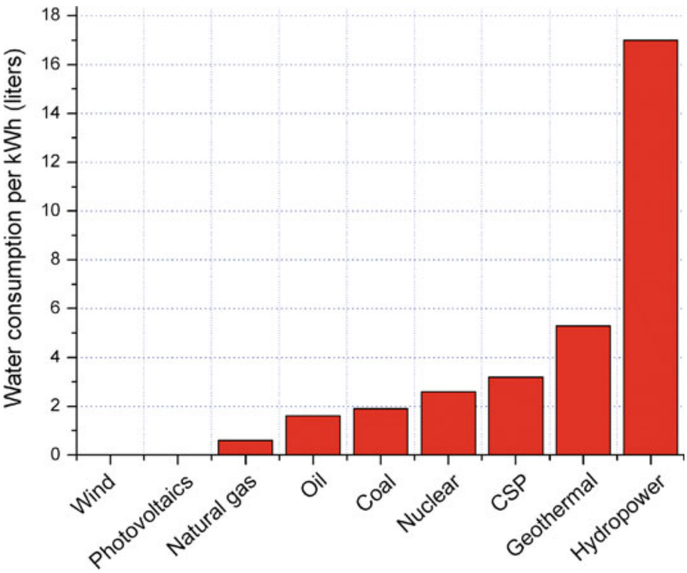

Fig. 2.10 Water consumption per kWh for different conventional and renewable energy technologies [26]

Finally, land utilization is also an important environmental parameter to be considered. It is important to recognize that there exists a significant gap in terms of power density per unit area between fossil fuels and renewable technology (Fig. 2.11) [27]. A coal mine or oil field, for instance, yields five to 50 times more

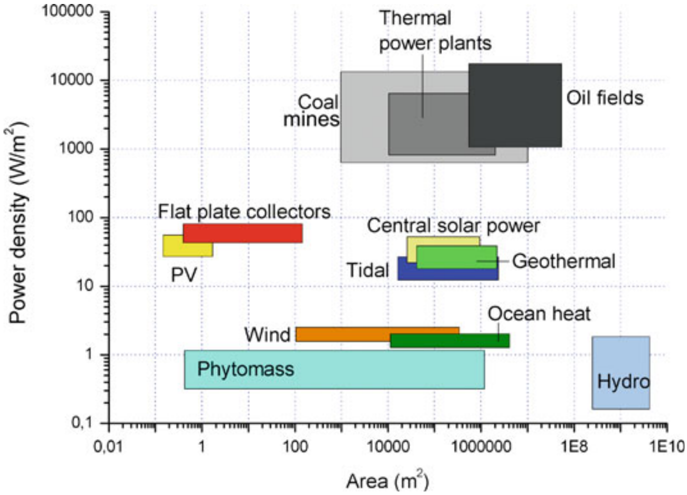

Fig. 2.11 Power density per unit area for different conventional and renewable energy resources and technologies [27]

power per square meter than a solar facility, 10–100 times more than a wind farm, and 100–1000 times more than a biomass plant. Even if the energy needed to extract, transport, and process coal is considered, it still yields 50 times more energy per unit of land than ethanol from corn and 10 times more than ethanol from sugarcane.

To achieve a low carbon energy development process it is necessary to move from coal and oil based energy utilities to lower carbon utilities that rely on natural gas, nuclear energy and renewables. Other indirect impacts and cost, mainly related to the use of water and land occupancy, should be also considered.

2.4 Main Country Indicators

The disparities between African and Latin American countries is not only evident in GDP and CO_2 emissions per capita (Figs. 2.6 and 2.7) but also in terms of population (2015), surface area and density of inhabitants per km^2 (Table 2.6) [1].

Another important issue for consideration is the ease of doing business in Africa and Latin America, particularly when foreign investment and technology is required for low carbon development. The World Bank every year publishes a report called Doing Business that can be considered the most important and influential tool for first approximation in investment decisions (Table 2.7) [28]. In 2015 the World Bank analysed 189 countries for ease of doing business and found that many of the most difficult countries to do business with are located in Africa. Some Latin American countries are also also included as very difficult countries in terms of doing business on the World Bank list.

In addition to the relationships highlighted above, there is also an interesting logarithmic correlation between the ease of doing business and electricity consumption per capita (Fig. 2.12) for the countries considered by the IEA statistics [3] (does not include countries involved in internal conflicts). We can conclude from these relationships that entrepreneurial activities increase as the electrification of a country increases. Chapter 3 provides more detail on this relationship.

2.5 Carbon Capture and Storage Systems

2.5.1 Overview

Carbon capture and storage (CCS) is being proposed as a key technology to avoid CO_2 emissions to the atmosphere from fossil fuel combustion related to electricity power plants. According to the latest available statistics (for the year 2014 [29]), 23,816 TWh of electricity production worldwide, 40.8% is obtained from coal,

Table 2.6 Ranking of African and Latin American countries in terms of population. Surface (S) area and population density (D) also included [3]

Country Name	Population (×1000)	S: km^2 (×1000)	D: h/km^{-2}
Africa	1,183,919	29,823	37
Nigeria	182,201	924	193
Ethiopia	99,391	1104	87
Egypt, Arab Rep.	91,508	1001	83
Congo, Dem. Rep.	77,266	2345	30
South Africa	54,957	1219	44
Tanzania	53,470	947	54
Kenya	46,050	580	78
Sudan	40,234	1879	21
Algeria	39,667	2382	17
Uganda	39,032	242	161
Morocco	34,378	447	75
Mozambique	27,978	799	33
Ghana	27,409	239	111
Angola	25,022	1247	18
Madagascar	24,235	587	40
Cameroon	23,344	475	48
Cote d'Ivoire	22,702	322	65
Niger	19,899	1267	15
Burkina Faso	18,106	274	64
Mali	17,600	1240	13
Malawi	17,205	118	142
Zambia	16,212	753	20
Zimbabwe	15,603	391	37
Senegal	15,129	197	74
Chad	14,037	1284	10
Guinea	12,609	246	49
South Sudan	12,340	644	18
Rwanda	11,610	26	459
Tunisia	11,108	164	67
Burundi	11,179	28	377
Benin	10,880	115	92
Somalia	10,787	638	17
Togo	7305	57	123
Eritrea	6536	118	56
Libya	6278	1760	4
Central African Republic	4900	623	8
Congo, Rep.	4.559	342	13
Liberia	4.397	111	39

(continued)

Table 2.6 (continued)

Country Name	Population (×1000)	S: km^2 (×1000)	D: h/km^{-2}
Mauritania	3.984	1031	4
Namibia	2.348	824	3
Lesotho	2.098	30	69
Botswana	2.039	582	4
Gambia, The	1.909	11	169
Guinea-Bissau	1.746	36	48
Gabon	1.711	268	6
Swaziland	1.268	7	73
Mauritius	1.261	2	618
Djibouti	886	3	38
Equatorial Guinea	778	8	28
Cabo Verde	504	4	125
Sao Tome and Principe	198	1	206
Latin America	591,564	20,203	30
Brazil	207,847	8516	24
Mexico	127,017	1964	63
Colombia	48,229	1141	43
Argentina	43,417	2780	15
Peru	31,377	1.285	24
Venezuela, RB	31,108	912	34
Chile	17,948	756	24
Guatemala	16,343	108	146
Ecuador	16,144	256	62
Cuba	11,390	109	102
Bolivia	10,725	1.098	10
Haiti	10,711	27	377
Dominican Republic	10,528	48	216
Honduras	8075	112	73
Paraguay	6639	407	17
El Salvador	6127	21	303
Nicaragua	6082	130	47
Costa Rica	4807	51	97
Panama	3929	75	52
Uruguay	3432	176	19
Guyana	767	214	4

21.6% from natural gas and 4.3% from oil, while the remaining electricity is derived from from nuclear, hydro and renewables. CO_2 can be captured and stored from other centralized emission sources, mainly in the fuel transformation sector and from plants located in the industrial sector.

Table 2.7 Easiness of doing business ranking in African and Latin American countries in 2015 [29]

Africa	No.	Latin America	No.
Mauritius	32	Mexico	38
Rwanda	62	Chile	48
Morocco	68	Peru	50
Botswana	72	Colombia	54
South Africa	73	Costa Rica	58
Tunisia	74	Panama	69
Zambia	97	Guatemala	81
Namibia	101	El Salvador	86
Swaziland	105	Uruguay	92
Kenya	108	Dominican Republic	93
Ghana	114	Paraguay	100
Lesotho	114	Honduras	110
Uganda	122	Brazil	116
Cabo Verde	126	Ecuador	117
Egypt, Arab Rep.	131	Argentina	121
Mozambique	133	Nicaragua	125
Tanzania	139	Suriname	156
Malawi	141	Bolivia	157
Cote d'Ivoire	142	Haiti	182
Mali	143	Venezuela, RB	186
Burkina Faso	143		
Ethiopia	146		
Togo	150		
Gambia, The	151		
Burundi	152		
Senegal	153		
Zimbabwe	155		
Benin	158		
Sudan	159		
Niger	160		
Gabon	162		
Algeria	163		
Madagascar	164		
Guinea	165		
Sao Tome and Principe	166		
Mauritania	168		
Nigeria	169		
Djibouti	171		
Cameroon	172		
Congo, Rep.	176		

(continued)

Table 2.7 (continued)

Africa	No.	Latin America	No.
Guinea-Bissau	178		
Liberia	179		
Equatorial Guinea	180		
Angola	181		
Chad	183		
Congo, Dem. Rep.	184		
Central African Republic	185		
South Sudan	187		
Libya	187		
Eritrea	188		

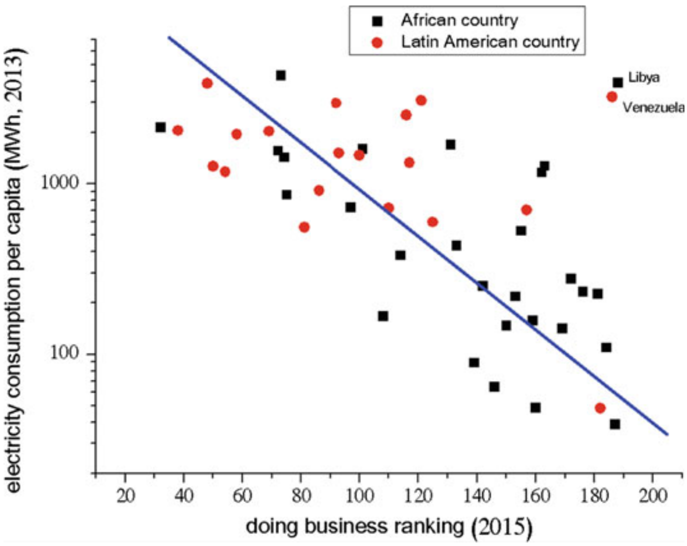

Fig. 2.12 Electricity consumption versus easiness of doing business in African and Latin American countries [3, 28]

The capture of carbon dioxide from centralized sources involves several steps:

(a) Capture of the carbon dioxide emitted from power plants, industrial plants, etc., including the transformation and compression of the emitted gases.
(b) Transportation of the CO_2 gas to a sink by means of pipes, vessels, appropriate vehicles, etc.
(c) Injection of the CO_2 in underground geological formations, such as oil or gas deposits that are already empty, stored in the oceans, etc.

In 1972, the first large-scale integrated project (LSIP) in Val Verde (Texas, USA) started operation. 15 large installations are currently operating worldwide,

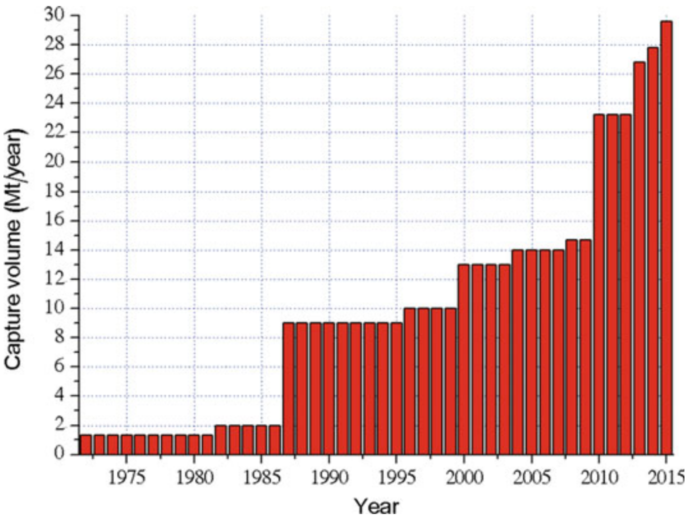

Fig. 2.13 Evolution of the world capture capacity for large CCS plants in operation (1972–2015) [30]

with most of them dedicated to enhanced oil recovery but also injecting into geological formations at different depths [30]. Ten of these plants operate with pre-combustion carbon capture technology, one with post-combustion carbon capture technology (explained below) and four with industrial separation processes, capturing about 30 Mt of carbon dioxide per year (Fig. 2.13).

The total CO_2 capture volume of all 15 projects in operation is about 0.1% of the annual CO_2 emissions from fuel combustion worldwide (last data available) [3]. However, between 80 and 120 Mt of CO_2 is sold commercially each year for a wide variety of applications (mostly for enhanced oil recovery, but also for chemical solvents, for decaffeination of coffee, carbonation of soft drinks, manufacture of fertilisers, refrigerants, plastics, etc.) and other applications can be valuable in future (enhanced algae cultivation, CO_2 concrete curing and bauxite residue carbonization) [26].

LSIPs are defined as those projects which involve the capture, transport and storage of CO_2 at a scale of: (i) not less than 800,000 tonnes of CO_2 annually for a coal-based power plant; and (ii) not less than 400,000 tonnes of CO_2 annually for other emission-intensive industrial facilities (including natural gas-based power generation).

2.5.2 State of the Art

There are four main technologies for CO_2 capture: (i) post-combustion capture, (ii) pre-combustion capture, (iii) oxy-fuelling, and (iv) chemical looping. The specific application of these technologies will vary depending on local and regional climatic conditions, specific fuel types and local variations.

The post-combustion capture of CO_2 from the exhaust gases of the combustion process, which has a CO_2 content between 2% and 25% [31], is usually performed at low pressure. The three main post-combustion processes are: (i) absorption, by the uptake of CO_2 into the bulk phase of another material (for example, dissolving CO_2 molecules into a liquid solution), the solvent is conducted to another compartment and heated to release the CO_2; (ii) adsorption, involving the selective uptake of CO_2 onto a solid surface surface, which is subsequently regenerated by lowering the pressure and/or increasing temperature to liberate the absorbed CO_2 (a claimed advantage of adsorption is that the regeneration energy should be lower relative to that of the absorption solvents); and (iii) membranes, by selectively permeating the flue gas through the membrane material (claiming low energy capture processes).

In the pre-combustion process the fuel is previously gasified producing a synthesis gas (syngas: a mixture of H_2 and CO). CO_2 removal from coal gasification syngas is a mature commercial process widely practiced throughout the world, mainly for removing CO_2 from natural gas to meet the purity standards. Then, the gas is cleaned from impurities that could damage the turbines, and the CO is mixed with steam to react and produce carbon dioxide and hydrogen. In this mix, the CO_2 is separated by an absorption process and prepared for transport and storage. The remaining gas, rich in oxygen, is mixed with additional oxygen and used to power a hydrogen gas turbine, which only produces water vapour as the exhaust. This turbine cycle with hydrogen is thermally more efficient for electricity production than the current ones [8]. Current commercially available pre-combustion CO_2 capture processes are based on the use of physical or chemical solvents. Typically all the solvents can accomplish greater than 90% CO_2 removal, under lower pressure than current post-combustion technology. Currently, there are a number of processes under development to demonstrate the feasibility of using pre-combustion in IGCC technology ("integrated gasification combined cycle") from coal and natural gas.

In the oxy-fuelling combustion process, fuel is burned in a pure oxygen environment instead of air, thereby avoiding the need of CO_2 separation in the exhaust gases as the content is up to about 90% [3]. If permitted by regulations, the raw, dehydrated flue gas may be stored directly without the need for further purification. Otherwise, the flue gas impurities (predominantly oxygen, nitrogen and argon) may be removed. One advantage of this technique is to facilitate the retrofitting of existing facilities, adding the ability to capture CO_2. The first electricity production plant using this technology became operational at Schwarze Pumpe in 2008. Oxyfuel combustion may be employed with solid fuels such as coal, petroleum coke, and biomass, as well as liquid and gaseous fuels.

The chemical looping combustion is still being developed to be applied in CCS, but its future looks promising, since it would consume much less energy than post-combustion technology and consequently improve the efficiency of the power plant compared to oxy-fuelling technologies. The chemical looping technique uses tiny particles of metal oxides as oxygen carriers, which make a loop between the combustion reactor and an air reactor. Thus, by reacting with fluids in a fluidized bed reactor (combustion reactor), the metal oxide particles introduce oxygen and again become metal. The oxygen and the fuel produce a mixture of CO_2 and water vapour in the reactor, which, after water condensation, the gas released is composed of nearly pure CO_2 that can be subsequently sequestered. Thus, the combustion takes place without any contact of fuel with air and, consequently, the exhaust contains no nitrogen content, making it easier to capture CO_2. The metal particles produced are transported to the other fluidized bed reactor where they react with air (air reactor) and re-oxidize, also releasing heat that can be used to increase the overall efficiency.

Transportation of CO_2 occurs largely in pipelines. There exists nearly 6,000 km of pipelines for pumping 50 Mtpa CO_2 worldwide, mainly in U.S. For geological storage under the seabed, the technology is more complex, but a plant with these characteristics is already operating (Snøhvit, Norway). In this facility, there are multiple lines originating from different CO_2 emissions plants and converging into a single larger pipe on the coast, where it is pressurized and connected to the geological location in the ocean where the CO_2 is stored.

Finally, geological storage of CO_2 can be produced by pumping the gas underground using several procedures, as illustrated in Fig. 2.14. One approach (process 1) is to store CO_2 in previous deposits of oil or gas that are already empty. CO_2 can also be used in so-called enhanced oil recovery. For this procedure, the injected CO_2 allows the extraction of oil not directly extracted by impulsion (process 2). CO_2 can also be injected in saturated sedimentary rock deposits of salt water (process 3). These rocks consist of alternating layers of water, silt, clay, etc. The CO_2 is trapped in the pores of the sand layers, in the capillaries of the clay layers, adsorbed on carbonaceous rocks, etc. It is also planned to store CO_2 in non-extractable coal veins (process 4) or to extract natural gas from these coal veins (process 5). Finally, there is the option for storage in basalt rocks, tar sands or in underground cavities (process 6). The storage of CO_2 in the subsurface of the ocean, usually at depths of 700 m or more, is also being considered.

In general, the technologies for CO_2 storage in deep geological formations are already highly developed, since they have been transferred from the exploration and extraction technologies for oil and natural gas. On the other hand, a storage capacity of 1,000–10,000 Gt CO_2 in salt deposits has been estimated, 600–1,200 Gt CO_2 in oil and gas fields, and 3–200 Gt CO_2 in coal veins to extract methane [32]. These magnitudes can be compared with 32.4 Gt CO_2 (Fig. 2.3) emitted by combustion of coal, oil and gas in 2014 (latest figures available) [3].

There is a significant effort in monitoring stored CO_2, using various technologies: (i) atmospheric techniques that utilize an infrared laser that is strongly absorbed by CO_2, so that the signal loss determines the CO_2 concentration; (ii) various near subsurface techniques that include geochemical analysis at shallow subsurface depths, measurement of CO_2 concentration in situ where gas is extracted and introduced into a chamber and topographic measurements of the electrical conductivity of materials below the surface; and (iii) deep subsurface techniques (in particular, geochemical)

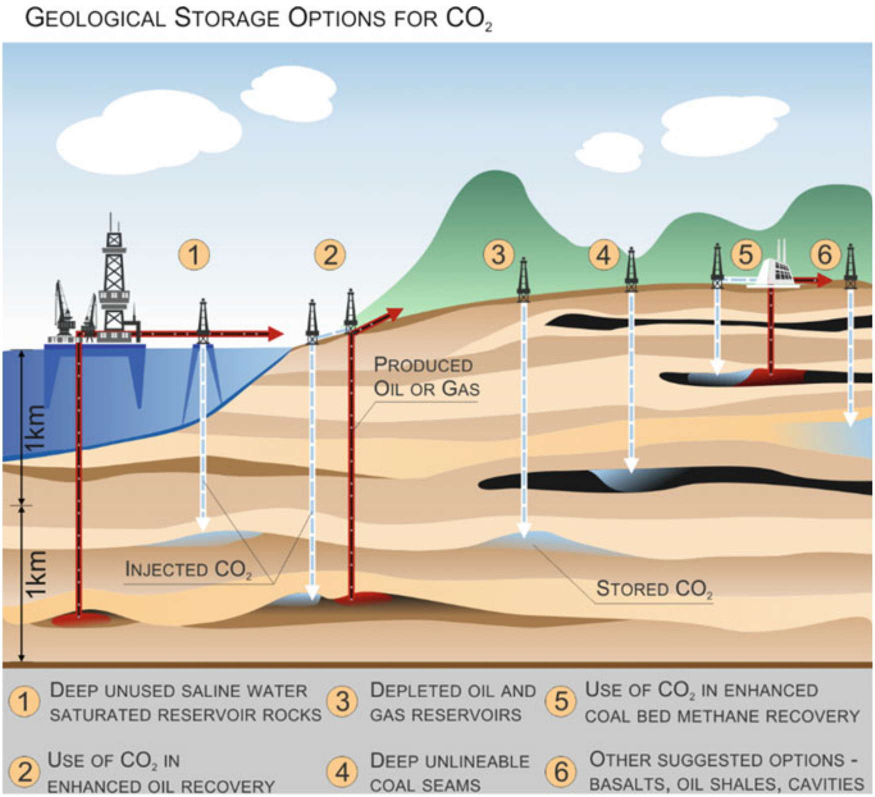

Fig. 2.14 Scheme of the different procedures for geological storage of CO_2 in the earth [10]

quite similar to those used in oil and natural gas fields, in which CO_2 migration can be studied using chemical tracers or measuring the variation of the signals from time-delay seismic analysis.

The IEA [33] published a study that shows the evolution of the thermal efficiency of various power plants based on coal and natural gas using different CCS technologies. These studies found efficiency losses ranging from 6.0 to 10.9%. In post-combustion technology, these efficiency losses are mainly due to the need to use steam to regenerate the solvent, and purification and compression processes of CO_2. In pre-combustion technology, the efficiency losses are attributed to the exothermic reactions losses that result from fuel conversion in the process prior to combustion. In oxy-fuelling combustion technology, the main efficiency losses are attributed to the need to feed the oxygen production unit. In chemical looping technology studies of these characteristics have not been currently detected.

2.5.3 Costs

The cost of CO_2 avoided reflects the cost of reducing CO_2 emissions to the atmosphere while producing the same amount of product, such as electricity, from a reference plant that does not include CCS technology. Some studies estimate that CCS costs varies from USD 57.9–94.0/tCO_2 [5], while in the larger CO_2 permits trade market (the European Union Emission Trading Scheme) the ton of CO_2 has been valued in the range EUR 5–7/tCO_2 in the last two years (USD 5.5-7.7/tCO_2) (Fig. 2.15). Finally, we have not found analyses of chemical looping process costs in the literature.

The largest uncertainty in the cost of large-scale demonstration plants is produced in the up-front capital costs. Incorporating CCS facilities increases capital investment costs by around 30% for an IGCC facility, and by 80% for the other coal and gas-based technologies. Total installed investment costs, including carbon capture technology, represent around 45–50% of the costs of electricity from coal-based CCS plants. Oxy-fuelling combustion has a lower relative cost on both levelised electricity costs and avoided CO_2 costs, compared to other CCS technologies.

CO_2 transport costs must be calculated for each individual installation, according to the transport technology used: pipelines similar to natural gas, compressed bottles in trucks, boats, etc. Costs have been evaluated for pipelines and ships [30] (Table 2.8). The investment cost of transport (1 m diameter pipe) vary from USD 0.80 million/km onshore to USD 1.34 million/km offshore.

The costs of geological storage cavities depend on many factors including depth below ground, the location (usually the location “offshore” is more expensive, etc.)

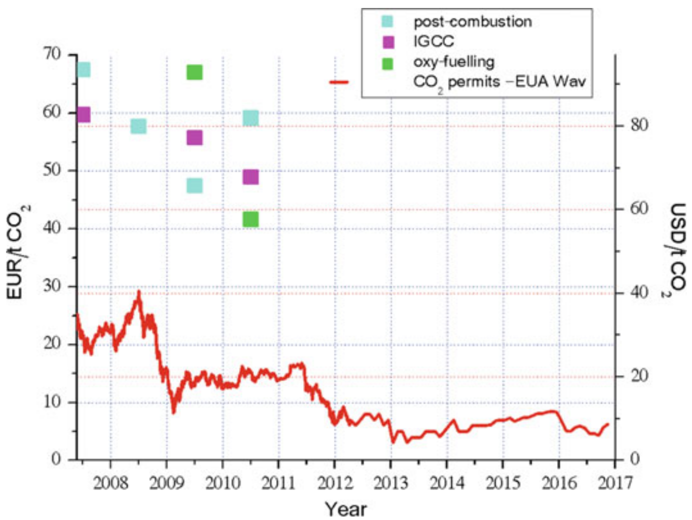

Fig. 2.15 CCS costs per ton of CO_2 for different technologies and evolution of the European Union Emission Trading Scheme for CO_2 permits

Table 2.8 Transport cost estimates for large-scale networks of 20 million tons per annum [30]

USD/t	180 km	500 km	750 km	1500 km
Onshore pipe	2.1	5.2	7.4	n/a
Offshore pipe	4.7	8.4	11.4	22.7
Ship (liq. incl.)	15.5	17.0	18.4	22.4

(Table 2.9). The CO_2 storage costs are highly variable, between USD 2.1–32.1/tCO_2 and can typically represent between 5 and 10% of the total cost of CCS [30]. Some estimations conclude that storage cost varies between USD 4.2–19.5/t CO_2 (Table 2.9).

The total CCS costs could be financially compensated in full and even produce an income if it is focused to value added applications. In this sense, CCS can be beneficial from an economic point of view for enhanced oil recovery (EOR). Thus, EOR activities have an estimated cost of 38–43 USD/tCO_2, and may recover a 5–23% more oil from oil fields [31], depending on reservoir conditions and oil—CO_2 miscibility. Also, other activities can add value to CO_2 capture, such as the manufacture of chemicals, especially synthetic gases.

The CCS costs can be translated to an increase of electricity costs. Thus, the additional costs due to CCS in electricity production range from USD 0.023–0.085/kWh, which would represent an increase of the electricity bill up to USD 8.5 cents per kWh with respect to current prices [3, 34].

Future CO_2 emission costs will depend on which technologies are more effective to capture, transport and storage of CO_2, the size of the CCS market, fuel prices, etc. The IEA estimates [35] that by 2030 a cost of USD 37.5/tCO_2 for CCS technologies, and the additional costs of electricity varying between USD 0.011–0.032/kWh. From these results, the International Energy Agency believes that it will be necessary to introduce an incentive of 50 USD/tCO_2 to facilitate the introduction of CCS in the energy sector [35]. However, as it has been exposed above, the evolution of prices for CO_2 emission permits in the European Climate Exchange market shows that the technology is still far from being attractive enough to be applied in power generation.

Thus, if we consider the data published by the IEA on CO_2 emissions per kWh in electricity production from natural gas, oil and coal power plants and they are adjusted to the daily price of the future of CO_2 emission rights [18] (Fig. 2.16), we find that, after the severe drop in the prices of those rights in the second half of 2008, prices do not cover the lowest costs estimates for CCS, including coal plants.

Table 2.9 Cost estimates for different storage cavities

USD/t CO_2	On-shore	Off-shore
Depleted oil and gas fields (legacy wells)	4.2	8.4
Depleted oil and gas fields (no legacy wells)	5.6	13.9
Deep saline formation	7.0	19.5

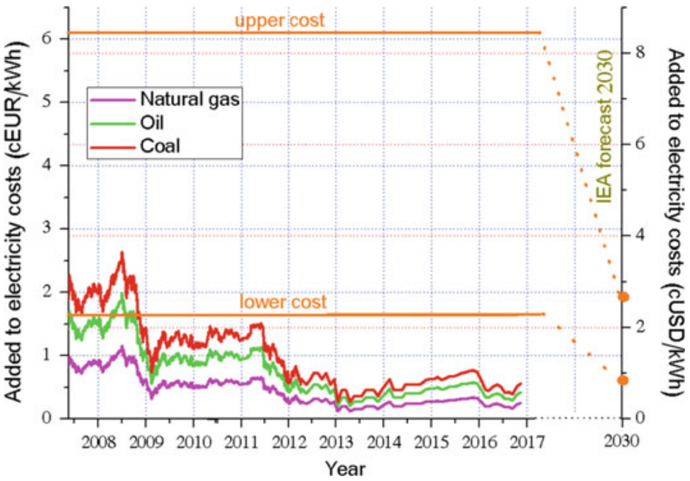

Fig. 2.16 Evolution of the additional costs to electricity production from coal, oil and natural gas, considering the variations in CO_2 emission permits in the European Union Emission Trading Scheme, and compared with current estimates for future costs of CCS exposed by the IEA

Also, if the current market price of future CO_2 permits remains relatively constant, it will be even more profitable in 2030 to purchase permits than to incorporate CCS technology into power plants.

Carbon taxes and emission trading schemes (ETS) have been implemented or scheduled for implementation in about 40 countries, mostly in the European Union, and 20 cities, mostly in North America and and East Asia, covering about a 12% of global emissions [26]. The combined value of carbon pricing instruments in 2015 was estimated at just under USD50 billion globally, of which almost 70% is attributed to ETSs and the reminder to carbon taxes. The existing carbon prices vary significatively, from less than USD1/tCO_2 in Mexico and Poland to USD130/tCO_2 in Sweden, but 85% of emissions covered are priced at <USD10/CO_2 [26]. In Africa, only South Africa is discussing a carbon tax. In Latin America, only the Chilean Parliament has approved (Sept 2014) the implementation of a national carbon tax that will put a price on emissions (equivalent to about USD 5/tCO_2eq) from 2017 onward, and applied to stationary sources with a thermal input capacity greater than 50 MW. Also the Mexican Ministry of Energy announced in February 2014 the possible development of an ETS in the energy sector, and Brazil is considering a ETS or carbon tax.

2.5.4 Carbon Emissions from CCS Based Power Plants

The IEA [8] published a study that shows the amount of CO_2 emitted, captured or avoided by power plants with different technologies for electricity production.

Therefore, adding CCS increases CO_2 emissions per kWh in power plants, since the thermal efficiency for these plants decreases (except in some cases where replaced technology is outdated and inefficient). Pre-combustion CCS technologies and post-combustion capture about 85–90% of emitted CO_2, while oxy-fuelling plants capture rate is about 90–97%. Also consider that each technology captures CO_2 with diverse purity, and variations in purity affect the value of the CO_2 produced.

Future technological trends are established according to the major challenges that CCS has for a principal role in mitigating climate change. In this respect, the biggest challenges lies in cost reductions and scaling by a factor of ten or more CCS facilities, as well as lower energy demand, especially in CO_2 capture processes.

2.6 Conclusions and Future Perspectives

Africa and Latin America possess tremendous potential for significant growth of renewable energy resources to support more than 23% of the 2015 global population. Much of this potential is derived from access to large land areas with more than 37% of the combined global surface area, the availability of abundant renewable resources (i.e., wind, water and solar), commitments to cut global emissions by 2030 and a growing recognition by some nations that low carbon development can enhance economic prosperity while reducing potential impacts on climate change. Also, Africa and Latin America produce more than 23% of the global renewable energy, with much of this energy provided by traditional biofuels and waste (36% of total global production) to support daily sustenance needs for heating and cooking rather than electricity production characteristic of nations with mature economies.

Africa and Latin America have diverse energy reserves that vary between nations but seldom achieve generation levels necessary for the long-term sustainment, or more importantly growth, of an individual national or regional economy. Current demand for energy in many nations is low (i.e., energy consumption per capita) so existing fossil fuel reserves are often adequate to meet existing needs and expected average growth in consumption. Coal, oil, natural gas and uranium are produced in both Africa and Latin America and nuclear power provides electricity to both. An energy paradox exists for Africa and Latin America driven largely by socioeconomics that suggests current energy resources are adequate to sustain the economy, but substantial energy resource development is necessary to improve regional GDP. Comparisons of GDP and CO_2 emissions per capita for the different countries in Africa and Latin America show only a few nations have been capable of increasing their GDP per capita while at the same time reducing their CO_2 emissions. Both regions have substantial opportunity to increase their GDP based on the expanded penetration of low carbon indigenous energy technologies into their infrastructure.

Three significant attributes of energy production that reflect environmental stewardship for Africa and Latin America include CO_2 emissions, water consumption and land utilization. As the relative contribution of renewable energy sources to total energy consumption increase, the life cycle CO_2 emissions produced from manufacturing, construction, O&M and disposal of renewable power plants will decrease. Water consumption per kWh for wind energy and photovoltaics is almost negligible, but can be substantial for other renewable technologies, mainly hydropower and geothermal. Land requirements may also vary depending on energy technology. Power density per surface occupied is a consideration that may reflect the impacts locally and regionally on extensive deployment of low CO_2. Other considerations that will influence future energy decisions for each African and Latin American nation include surface area, population and population density, and ease of business transactions. As the ease of transactions within the business environment improves there is likely to be greater diversification of energy sources and expansion of entrepreneurial activities.

Collectively, energy, environmental, economic and business parameters suggest that Africa and Latin America are regions with their own peculiarities, but each region is evolving to achieve higher living standards. An evolution to a low carbon energy future for these countries will require access to resources and technology and to finance and international trade. This future is possible and necessary for the global community.

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